A Comprehensive Analysis of the Spatial and Seasonal Shifts in Tornado Activity in the United States

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(Manuscript received 24 August 2023, in final form 9 April 2024, accepted 25 April 2024)

ABSTRACT: Recent articles have shown that the long-portrayed "tornado alley" in the central plains is not an accurate portrayal of current tornado frequency over the United States. The greatest tornado threat now covers parts of the eastern United States. This paper shows that there has been a true spatial shift in tornado frequency, dispelling any misconceptions caused by the better visibility of tornadoes in the Great Plains versus the eastern United States. Using F/EF1+ tornadoes (the dataset least affected by increasing awareness of tornado locations or by changing rating methods), a 1° × 1° grid, and data for the two 35-yr periods 1951–85 and 1986–2020, we show that since 1951, by critical measures (tornadogenesis events, tornado days, and tornado pathlength), tornado activity has shifted away from the Great Plains and toward the Midwest and Southeast United States. In addition, tornadoes have trended away from the warm season, especially the summer, and toward the cold season since 1951. Annual trends in tornadoes by season (winter, spring, summer, and autumn) confirm this. All of the increase in F/EF1+ tornadoes in the eastern United States is due to an increase in cold season tornadoes. Tornadoes in the western United States decreased 25% (from 8451 during 1951–85 to 6307 during 1986–2020), while tornadoes in the eastern United States. increased 12% (from 9469 during 1951–85 to 10 595 during 1986–2020). The cities with the largest increases and decreases in tornado activity since 1951 are determined.

SIGNIFICANCE STATEMENT: This paper quantifies in many ways (tornadoes, tornado days, and pathlength) the geographical shift in tornadoes from the central to the eastern United States and from the warm season to the cold season, since 1951. Where and when tornadoes most frequently occur is significant not only for the research and operational meteorology communities but also for public perception and risk awareness. Some research studies have shown that tornado casualties are more likely in the eastern United States and the cold season because of preconceived notions of a "tornado alley" in the Great Plains and a "tornado season" in the spring. Publication of the results of this research might help ameliorate this problem.

KEYWORDS: Tornadoes; Trends; Emergency preparedness

1. Introduction

There is evidence that the pattern of risk posed by tornadoes is changing, which is of obvious importance to the people of the United States, and the risk posed by tornadoes to people in the United States remains significant. Tornado fatalities per million people in the United States, which decreased dramatically for many decades (e.g., Brooks and Doswell 2002), have held fairly steady since 1985 (Ashley and Strader 2016). In addition, the increase in casualties due to intense tornadoes hitting more densely populated areas is greater than linear (Elsner et al. 2018), and there have been a number of "near-misses" where violent (F/EF4–5) tornadoes nearly hit populated areas (Hatzis et al. 2019). Several articles have definitively shown that tornado risk is not only confined to the traditional "tornado alley" of the Great Plains (GP) (e.g., Thom 1963) but also includes more densely populated areas of the Southeast and parts of the Midwest (e.g., Concannon et al. 2000; Ashley 2007; Dixon et al. 2011; Smith et al. 2012; Kellogg 2013). Coleman and Dixon (2014) showed that the Southeast United States had the largest risk in the United States from significant tornadoes (Hales 1988) during the period 1973–2011. However, that area of maximum risk has apparently not been stationary. Agee et al. (2016) first showed that tornadogenesis events had shifted eastward into more densely populated regions of the United States, including the Southeast. Ashley and Strader (2016) and Moore and DeBoer (2019) showed similar results. Gensini and Brooks (2018) went further and showed that an eastward shift in the atmospheric environments favorable for tornadoes, using the significant tornado parameter (STP; Thompson et al. 2003), occurred between 1979 and 2017. The STP has been shown to correlate well with tornado reports (e.g., Gensini and Brooks 2018; Gensini and Bravo De Guenni 2019).

In addition, there has been a seasonal shift in tornadoes, away from the "warm season," defined herein as March through August, and toward the "cold season," defined herein as September through February. Some studies have already identified an increase in tornado activity in recent years during the heart of the cold season, primarily in the Southeast United States (e.g., Childs et al. 2018). Others have pointed

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DOI: 10.1175/JAMC-D-23-0143.1

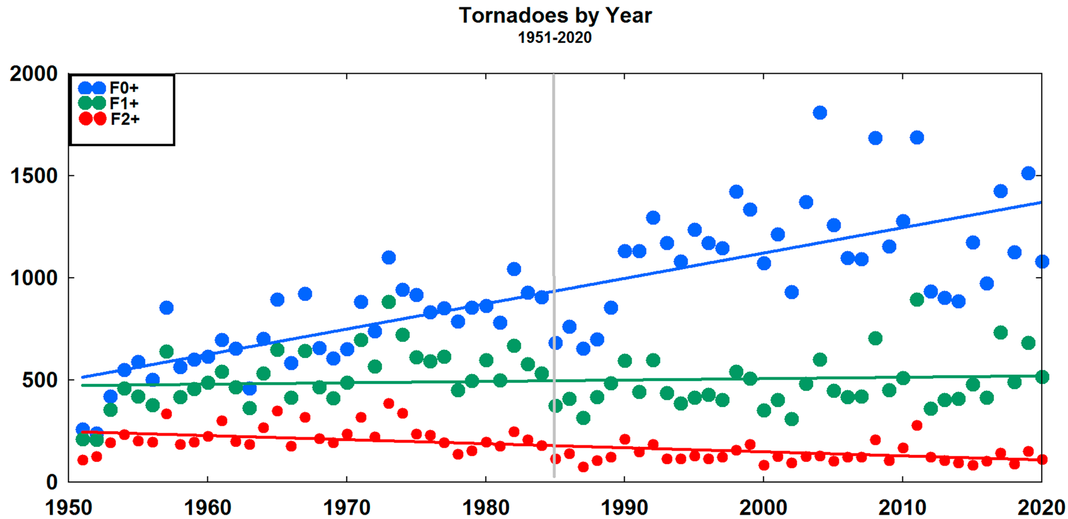


FIG. 1. Annual counts of F/EF0+ tornadoes (blue dots), F/EF1+ tornadoes (green dots), and F/EF2+ tornadoes (red dots) (1951–2020). Best-fit linear trend lines are shown. The gray vertical line denotes 1985, the dividing line between periods 1 and 2.

out the potentially higher risk to people of cold season tornadoes because of their relative infrequency (e.g., Fike 1993; Simmons and Sutter 2008) and the occurrence of holiday activities during the cold season (Childs and Schumacher 2018), both of which could lead to people being caught off guard.

Although the causes of any geographic and seasonal shifts in tornado activity are not the focus of this paper, earlier climate models indicated an increase in CAPE over the United States and therefore an implied increase in severe local storms, including tornado activity (e.g., Trapp et al. 2007, 2009; Diffenbaugh et al. 2013). More recently, Bercos-Hickey et al. (2021) found that, in numerical models of the late twenty-first-century climate, tornado environments may be more favorable during winter and at night, and these are more likely in the eastern United States (e.g., Childs et al. 2018). They also found that tornado environments may be less favorable in spring by the late twenty-first century; this could affect both the central and eastern United States. Trapp and Hoogewind (2018) found that decreasing Arctic sea ice may lead to fewer tornadoes in summer (when GP tornadoes are more favored, e.g., Dixon et al. 2014). Numerical simulations by Gensini and Mote (2015) indicate an increase in tornadoes in the United States, but primarily in the early part of the primary severe weather season and in the Southeast and Midwest. Interestingly, Fujita et al. (1975) found an oscillating pattern in the centroid of U.S. tornado fatalities, with a period of 40–45 years, and Boruff et al. (2003) found that the geographic center of tornado activity in the United States shifted southeastward between 1950 and 1999. Finally, there is the possibility that the more recent negative phases of the Pacific decadal oscillation (e.g., Biondi et al. 2001) and the Atlantic multidecadal oscillation (e.g., Marullo et al. 2011) may be playing some role in the geographical center of tornado activity, meaning that changes observed could reverse in future years.

In this paper, the eastward shift in tornado activity over time suggested by previous studies is examined by comparing two 35-yr periods, 1951–85 and 1986–2020. This shift is analyzed using 1) the annual number of tornadogenesis events (also referred to herein as “tornadoes”), 2) the annual number of tornado days, and 3) the annual pathlength. Even though F/EF0 tornadoes are excluded from the study to attempt to maintain time stability in tornado reports, there has been a growing number of reported F/EF1 or greater tornadoes associated with quasi-linear convective systems (QLCSs), mainly in the eastern United States. Finally, as significant tornadoes (F/EF2 and stronger) are least likely to have been missed in the tornado records since the Fujita scale was used in real-time damage ratings starting in 1973, the change in those between the subperiods 1973–96 and 1997–2020 is also examined.

2. Data and methods

a. General methodology

The main data source utilized in this study is the Storm Prediction Center (SPC) severe weather database (e.g., Schaefer and Edwards 1999), which contains tornadogenesis location, date and time, rating, pathlength, and width for tornadoes in the United States between 1950 and 2020. The SPC data are examined for two 35-yr periods, period 1 (1951–85) and period 2 (1986–2020); 1950 was omitted, so each period would be equal in length. Figure 1 shows the yearly counts of tornadoes that were rated greater than F/EF1 (F/EF1+) and F/EF2+ tornadoes and the yearly count of all tornadoes (F/EF0+). Clearly, the nearly tripling of F/EF0+ tornadoes is not realistic but instead associated with much better spotting techniques (e.g., Verbout et al. 2006; Coleman et al. 2011; Kunkel et al. 2013) and improved National Weather Service (NWS) warning verification procedures (e.g., McCarthy and Schaefer 2004); these NWS procedures include the installation of the nationwide network of WSR-88D radars during the 1990s and the addition of dual-polarization capabilities to the WSR-88D in 2011–13 (since then, "tornado debris signatures," e.g., Ryzhkov et al. (2005), have become verification of a tornado, with or without a ground sighting). The explosion of social media over the past ~15 years must also be considered. However, there is a slight decrease with time in F/EF2+ tornadoes reported in the database, especially from pre- to post-1973. This may be at least partially caused by the fact that tornadoes began being evaluated based on the Fujita tornado rating scale in their immediate aftermath in 1973; tornadoes before this time were likely overrated due to the use of news clippings, etc. (e.g., Schaefer and Edwards 1999; Brooks and Craven 2002; Anderson et al. 2007).

For each 35-yr period listed above, the number of tornadogenesis events, the number of tornado days, and the total pathlength (km) within each 1° × 1° box in the United States between 25° and 50°N and between 67° and 106°W (approximately east of the Continental Divide) were determined and then smoothed using a Gaussian 3 × 3 filter (e.g., Ashley 2007). The change of the Gaussian distribution for each parameter, from period 1 to period 2, was also determined for each variable in each grid box. Note that a given tornado only has one "tornadogenesis" or "tornadogenesis event" in this paper, no matter how many grid boxes the tornado passes through.

Two equal areas, each containing 60 1° grid squares, were designated. The first is the GP, defined as the area between 32° and 41°N and between 95° and 100°W. The Southeast (SE) is defined as the area between 31° and 36°N and between 85° and 94°W (see Fig. 2a). The statistical significance of changes in yearly tornadogenesis events within each of these areas was evaluated using the bootstrap method (e.g., Diciccio and Romano 1988; Agee et al. 2016).

Given that the annual number of significant tornadoes has been decreasing since the Fujita scale was implemented in real-time storm surveys in 1973 (e.g., Schaefer and Edwards 1999; Anderson et al. 2007; Coleman and Dixon 2014), the number of significant tornadoes and their pathlength during the two subperiods 1973–97 and 1997–2020 were determined and compared. Temporal tornadogenesis trends in the SE and GP were analyzed, and the grid boxes with the greatest increase and decrease between the two periods were located.

The shift in tornadoes away from the warm season and toward the cold season was evaluated first using best-fit linear trends in nationwide annual F/EF1+ tornadogenesis events during each of the four seasons (spring, MAM; summer, JJA; autumn, SON; and winter, DJF). The slope of the best-fit linear trends and therefore the changes in annual tornado counts during each season, from 1951 through 2020, were calculated. The locations of tornadoes by season and the change from period 1 to period 2 were also examined. The statistical changes in tornado occurrence across the seasons were determined, and differences between seasons allowed inferences to be made about the quantitative shift in tornadoes away from warm seasons and toward cold seasons.

b. Caveats regarding the SPC database

There have been considerable changes over the years in the methods used to count, measure, and assign ratings to tornadoes.

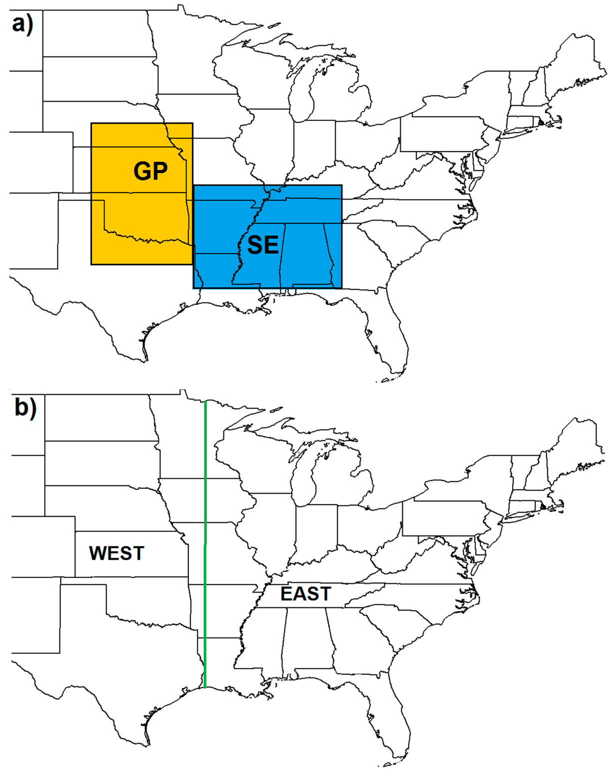


FIG. 2. (a) Two equal areas defined as GP and SE in this study. (b) The United States divided into "west" and "east" sections by 93.5°W longitude.

Prior to 1973, most tornado information in NWS Storm Data, and thus the SPC database, was based upon newspaper clippings and photographs. Some tornadoes that did not cause substantial damage may be missing entirely from the tornado database. F-scale ratings for pre-1973 tornadoes were estimated after-the-fact based upon the descriptions of damage listed in Storm Data. Sometimes, newspaper stories sensationalized damage, resulting in the overrating of some pre-1973 tornadoes (e.g., Schaefer and Edwards 1999; Brooks and Craven 2002; Anderson et al. 2007). Starting in 1973, NWS offices began assigning F-scale ratings in real time, but some of these, especially in the 1970s and 1980s, were still based upon newspapers, while others had detailed damage surveys. As the NWS implemented the WSR-88D radars during the 1990s, NWS offices became more active in performing damage surveys. There still may have been some variations between NWS offices and over time within a given office, in the frequency and detail of damage surveying. Damage descriptors were somewhat vague and subjective in the original F scale, likely introducing inaccuracies in F-scale ratings in the SPC database. In 2007, the enhanced Fujita scale was adopted for real-time assessment of tornado damage. This scheme made the rating tornadoes more objective and has likely reduced the frequency of assigning higher-end ratings. These same capabilities have also likely resulted in greater accuracy of pathlengths in the 1986–2020 data than in the 1951–85 data.

It is impossible to fully adjust for all potential errors in the tornado database. Elimination of F/EF-0 tornadoes from our analysis helped reduce the impact of the underreporting of weak tornadoes during 1951–85. Seasonal spatial comparisons were not likely compromised, as errors would be fairly consistent year-round. Our analyses of F/EF-2 and stronger tornadoes in the 1973–96 versus 1997–2020 periods should be less subject to the impacts of tornado database inconsistencies.

3. Initial geographical results

a. Tornadoes

First of all, the annual number of F/EF1+ tornadogenesis events occurring in each 1° × 1° grid square over the contiguous United States to the east of the Continental Divide, during period 1 (1951–85) and period 2 (1986–2020), was determined and smoothed using a Gaussian 3 × 3 filter. These results, and the change between the two periods, are shown in Fig. 3. The classic tornado alley in the GP, from northern Texas through Oklahoma and eastern Kansas, is apparent for period 1 (1951–85) in Fig. 3a. The nonsmoothed maximum number of annual tornadoes per grid box during period 1, 3.7, was located in south-central Oklahoma. Most of the tornado alley defined above had at least 1.5 annual tornadoes per grid box, and its primary area in Texas and Oklahoma had at least two annual tornadoes per grid box. There were scattered additional regions of 1.5–2 annual tornadoes per grid box during time period 1, including south-central Nebraska, southern Mississippi, north-central Alabama, and central Indiana.

An apparent eastward shift in tornadogenesis is shown during period 2 (1986–2020) in Fig. 3b. The area in which at least 1.5 annual tornadoes per grid box occurred, and which defined the classic tornado alley during time period 1, became larger and extended from eastern Oklahoma and extreme eastern Texas through Alabama, Tennessee, and the western Ohio Valley. The traditional tornado alley in the GP is no longer apparent in period 2. The primary area for tornadoes (at least two annual tornadoes per grid box) extended from northern Louisiana into southern Mississippi and northern Alabama for 1986–2020. There was a notable unsmoothed maximum in southern Mississippi with a magnitude of 4.6 annual tornadoes per grid box, higher than any magnitude during period 1.

The largest decrease in annual tornadoes from period 1 to period 2 (Fig. 3c) was from eastern Kansas through Oklahoma and into northern Texas. The decrease of one annual tornado per grid box in southern Oklahoma and northern Texas represents a 40% decrease in annual tornado activity from period 1 to period 2. The largest increase was in southern Mississippi, but the area of significant increase (at least 0.5 tornado events per grid box per year) extended from Louisiana to western Kentucky. This represents about a 25% increase in annual tornado activity.

b. Tornado days

Next, the Gaussian-smoothed annual number of tornado days in each 1° × 1° grid square was calculated over the same area for periods 1 and 2. These results, and the change between the two periods, are shown in Fig. 4. The classic

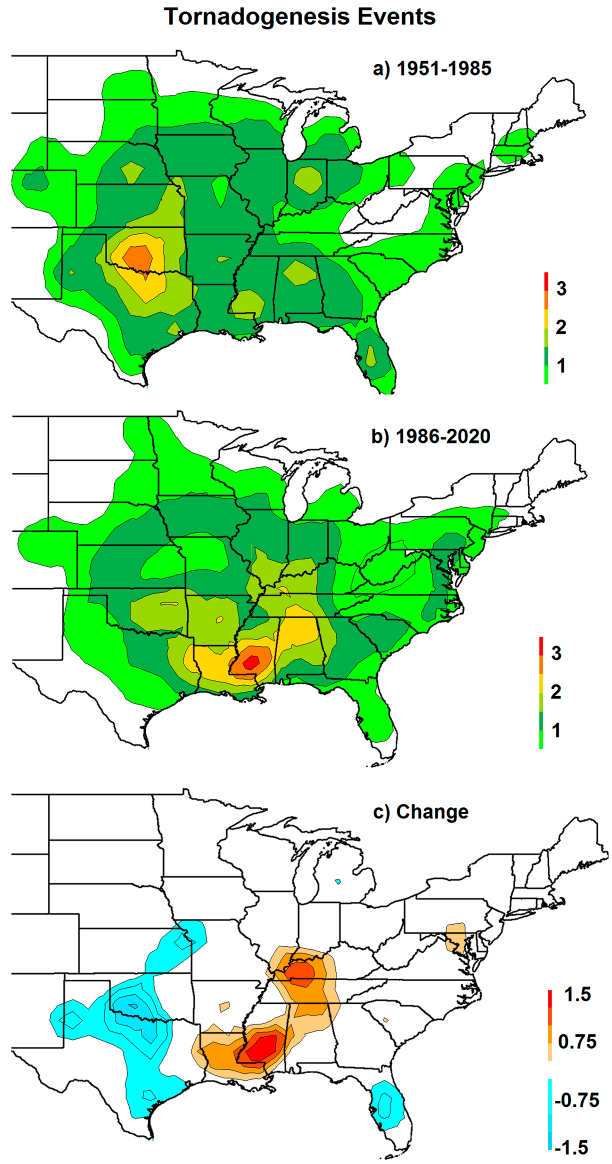


FIG. 3. Smoothed tornadogenesis events per 1° × 1° grid square during (a) period 1 (1951–85) and (b) period 2 (1986–2020). (c) Change in smoothed tornadogenesis events per grid square from period 1 to period 2.

tornado alley in the GP is also pronounced in tornado days during period 1 (Fig. 4a); however, tornado days were a bit more evenly spread out to include the Southeast and Midwest during period 1. Most of the tornado alley defined above had at least 1.25 annual tornado days per grid box, and its center in Oklahoma had at least two annual tornado days per grid box. However, parts of the Southeast and Indiana had 1.25–1.50 tornado days per grid box. The maximum unsmoothed value of 2.8 for period 1 was also located in south-central Oklahoma.

The maximum in annual tornado days was clearly in the Southeast United States during period 2, with the areas having

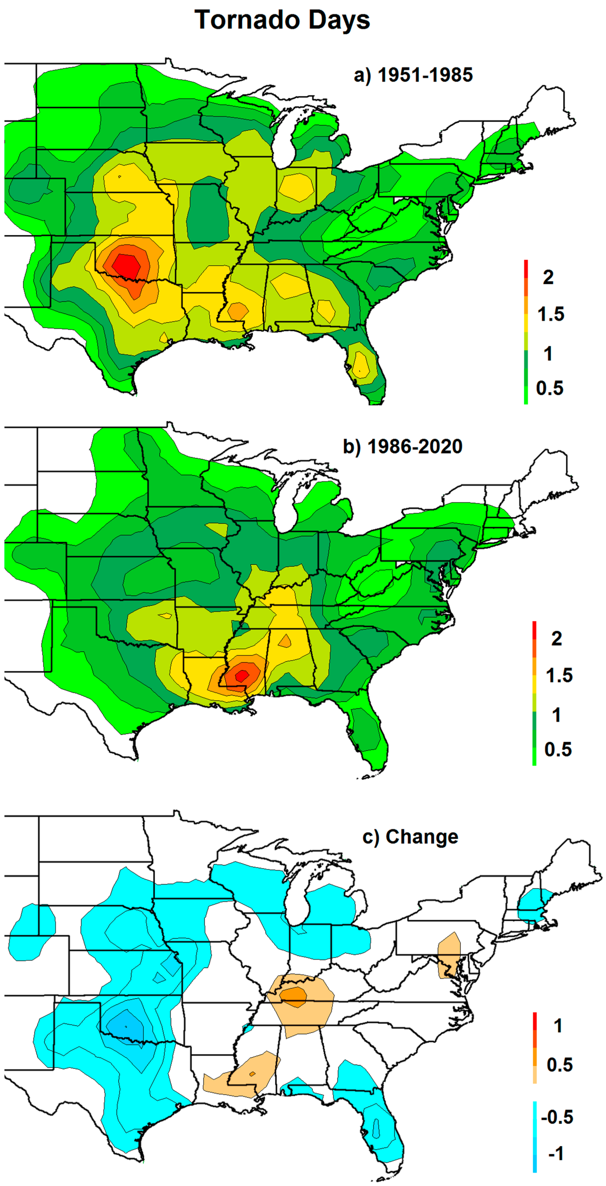


FIG. 4. Smoothed tornado days per 1° × 1° grid square during (a) period 1 (1951–85) and (b) period 2 (1986–2020). (c) Change in smoothed tornado days per grid square from period 1 to period 2.

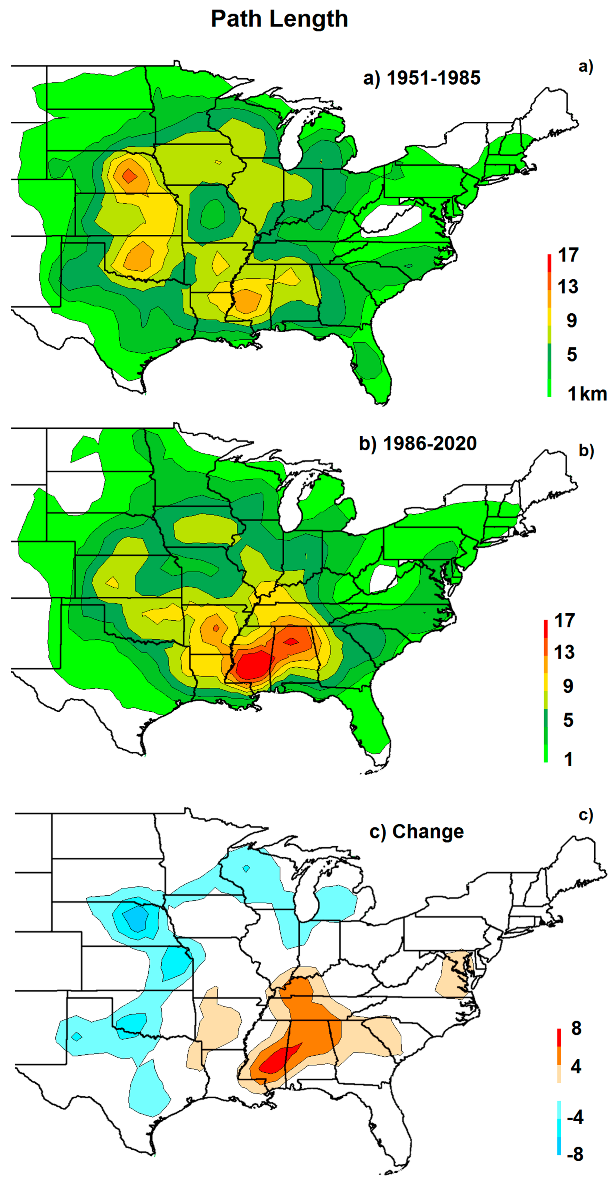


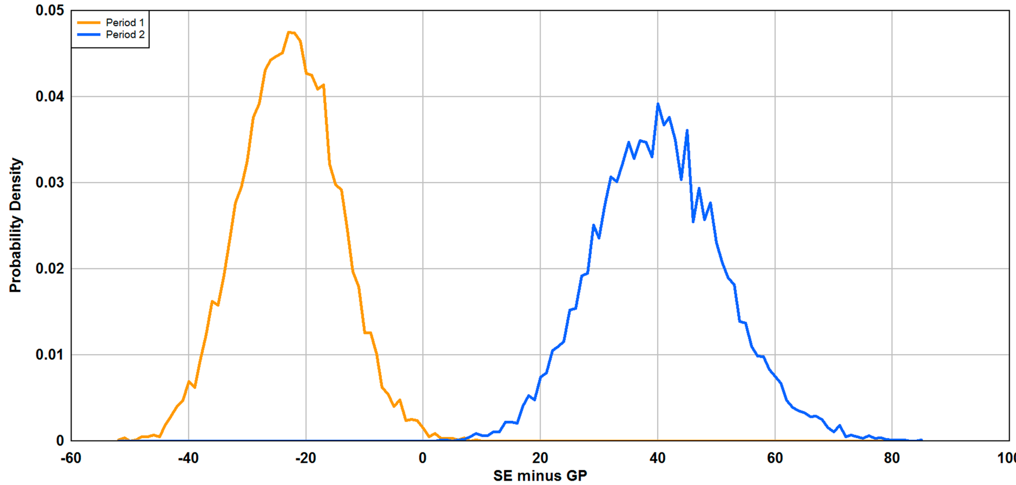
FIG. 5. Smoothed annual tornado pathlength (km) within 40 km of a point during (a) period 1 (1951–85) and (b) period 2 (1986–2020). (c) Change in smoothed tornado pathlength (km) within 40 km of a point from period 1 to period 2.

at least 1.25 annual tornado days per grid box extending from Louisiana through Mississippi, northern Alabama, and into Tennessee and Kentucky (Fig. 4b). The maximum unsmoothed value for period 2 was 2.9 annual tornado days per grid box in southern Mississippi.

The eastward shift is also apparent in tornado days. A large area from Nebraska to Texas had a decrease in tornado days of at least 0.5 per grid box per year from period 1 to period 2 (Fig. 4c). However, annual tornado days increased in southern Mississippi and also from middle Tennessee to western Kentucky. The largest unsmoothed decrease in annual tornado days in a grid box was in central Oklahoma (−1.7), while the largest increase was in middle Tennessee (1.0).

c. *Tornado pathlength*

Tornado pathlength likely provides a better measure of tornado risk than tornadogenesis events or tornado days, since a 100-km tornado path threatens 100 times as much land as a 1-km tornado path, all else being equal (e.g., Coleman and Dixon 2014). However, a longer duration of exposure occurs with slower-moving tornadoes, and it is not entirely clear how a faster-moving tornado with shorter duration of tornadic winds at any one location compares to a slower-moving tornado that lasts longer at one location. Remaining consistent with Coleman and Dixon (2014) and the SPC's probabilities of tornadoes within 25 mi (40 km) of a point, Fig. 5 shows



1951-1985 SE-GP	
Mean	-22.8667
Stdev	8.366417
Skew	0.052262
1%	-41.8574
5%	-36.63
95%	-9.08571
99%	-2.88571

1986-2020 SE-GP	
Mean	40.14327
Stdev	11.0998
Skew	0.182895
1%	15.77114
5%	22.31429
95%	58.97143
99%	67.80029

FIG. 6. Probability density functions for SE minus GP tornadoes from the 10 000 trials run for period 1 (orange) and period 2 (blue).

tornado pathlength within 40 km of a point for periods 1 and 2, once again on a 1° × 1° grid and smoothed using a 3 × 3 Gaussian filter.

The classic tornado alley in the GP is still apparent in period 1 (Fig. 5a), but values in parts of southern Mississippi and Alabama are similar (at least 9 km of annual tornado pathlength within 40 km of a point). The largest unsmoothed value during period 1 was actually in southern Mississippi (18.7 km of annual pathlength within 40 km of a point). There is still a remnant of the traditional tornado alley in period 2, but clearly the area with the greatest pathlength of tornadoes is in the Southeast, with values of at least 9 km of annual tornado pathlength within 40 km of a point covering most of Arkansas, northern Louisiana, Mississippi, Alabama, Tennessee, and western Kentucky (Fig. 5b). There was a particularly large pathlength zone from southern Mississippi to northern Alabama, with at least 13 km of annual tornado pathlength within 40 km of a point; the highest unsmoothed value, 27.2, was once again in southern Mississippi. The change in annual pathlength (Fig. 5c) was similar in morphology to the change in annual tornadoes (Fig. 3c).

d. Statistical significance

To determine the statistical significance of the change in tornadoes from period 1 to period 2, in the two equal areas defined in section 2 as the SE and GP (see Fig. 2a), the bootstrap method was employed (e.g., Diciccio and Romano 1988; Agee et al. 2016). For period 1, the annual number of tornadoes in the GP and the SE was determined, and a random year from each dataset (GP and SE) was selected and the difference between the two was calculated. This process was repeated 35 times, and the mean of the 35 difference values (SE minus GP) was stored. That entire process was then repeated 10 000 times, producing 10 000 mean difference values (see Agee et al. 2016, their Fig. 12). A probability distribution of difference values was then determined for period 1 (see Fig. 6), and the entire process described above was repeated for period 2. Since zero is not in the interval between 5th and 95th percentiles during either period and the 99th percentile for period 1 is less than the 1st percentile for period 2, the change in tornadoes from the GP to the SE from period 1 to period 2 is statistically significant.

4. Results using significant tornadoes only

Significant tornadoes (those rated F/EF2 or higher) were shown to be a fairly steady (or slightly declining) database in the United States both since 1950 (Fig. 1) and since 1973, when near-real-time rating of tornadoes began. It is also unlikely for an F/EF2+ tornado to have been missed during this time. Since 1973, the number of significant tornadoes has declined slowly (Figs. 7a,b), while the annual pathlength of significant tornadoes has declined to a lesser extent (Fig. 7c). It is not known how much of this change over time is due to a reduction of the number of tornadoes rated F/EF2+ due to 1) improved damage survey methods over recent decades and/or 2) the use of the enhanced Fujita scale beginning in 2007 [McDonald et al. 2004; Texas Tech University (TTU) 2006; Edwards et al. 2021].

The dataset with the least decrease (1973–2020) is pathlength (about 34%), so to examine the eastward shift in significant tornadoes, the average annual number of F/EF2+ tornadoes and the average annual pathlength of these tornadoes were determined for the two 24-yr subperiods 1) 1973–96 and 2) 1997–2020. The temporal changes between these subperiods are shown in Fig. 8. Even during this more recent period (1973–2020), an eastward shift in significant tornadoes and the pathlength of significant tornadoes are apparent. The overall national decrease in significant tornadoes is apparent in Fig. 8a, with a large decrease in northern Texas and Oklahoma and little increase in Mississippi and Alabama. However, the steadier database, pathlength of significant tornadoes, shows a decrease in much of the GP and an increase in much of the eastern United States, primarily the Southeast and western Ohio Valley, from 1973–96 to 1997–2020.

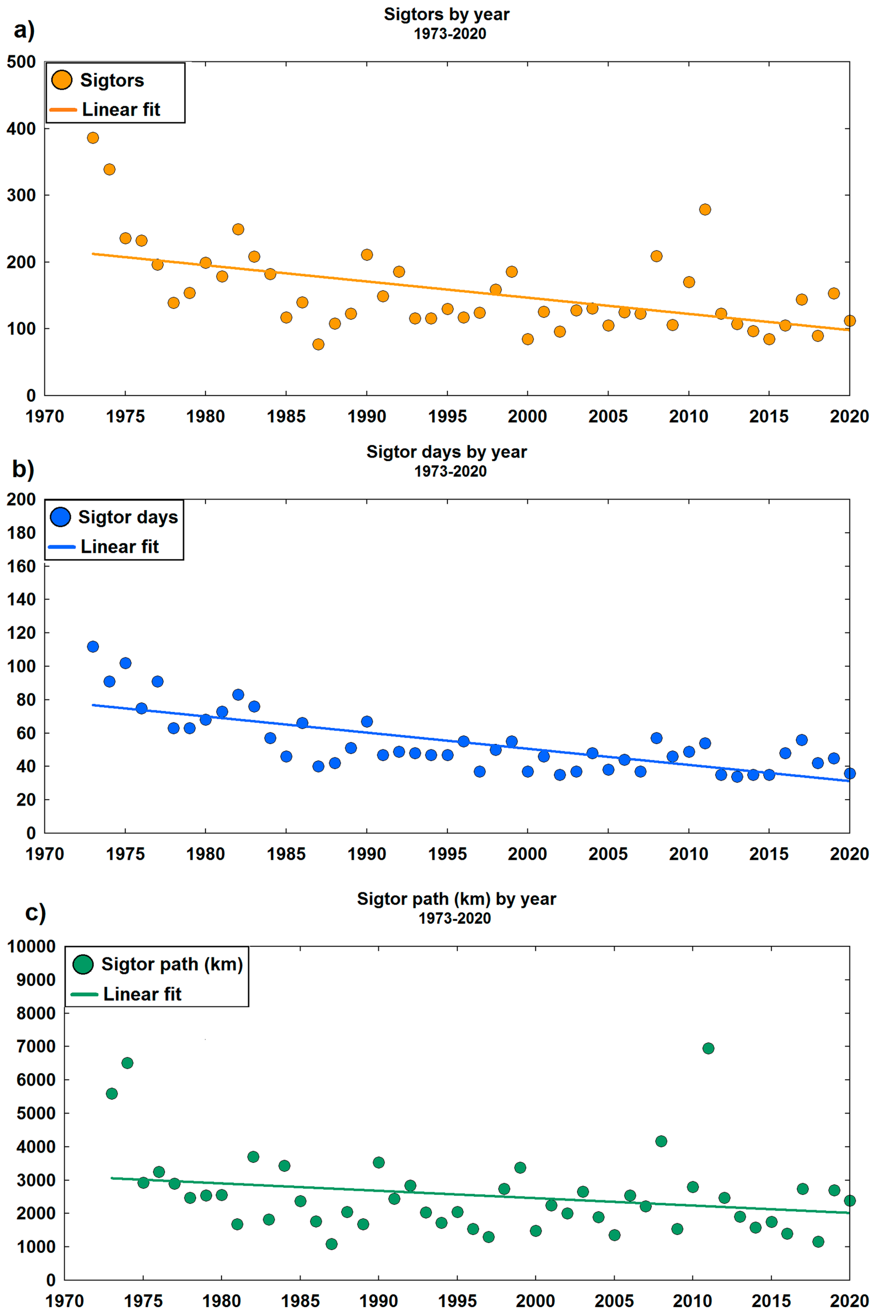


FIG. 7. (a) Significant tornadoes, (b) significant tornado days, and (c) significant tornado pathlength (km) by year, 1973–2020, with best-fit linear trend in each.

5. Locations with largest temporal changes

The 10 latitude/longitude boxes on the Gaussian-smoothed 1° × 1° grid over the United States to the east of the Continental Divide with the largest increase and largest decrease in tornadogenesis events and tornado pathlength are shown in Fig. 9. Most of the grid boxes with the largest increase in tornadoes are in southern Mississippi, middle Tennessee, and southwestern Kentucky, while those with the largest decrease in tornadoes are in northern Texas and southern Oklahoma. The grid box with the single largest increase in tornadoes includes the city of Jackson, Mississippi, while the box with the single largest decrease includes Cleburne, Texas.

The grid boxes with the largest change in pathlength mainly stretch from southern Mississippi into northern Alabama; the largest decreases in pathlength are in southern Oklahoma and in parts of Nebraska and Kansas. The grid box with the single

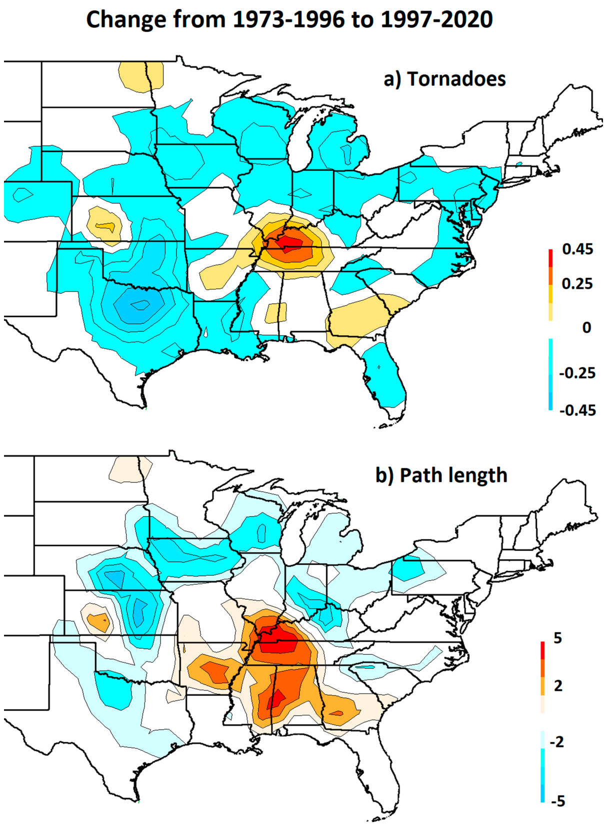


FIG. 8. The change from subperiod 1973–96 to subperiod 1997–2020 in (a) annual significant tornadoes per 1° × 1° grid square and (b) annual pathlength (km) of significant tornadoes within 40 km of a point.

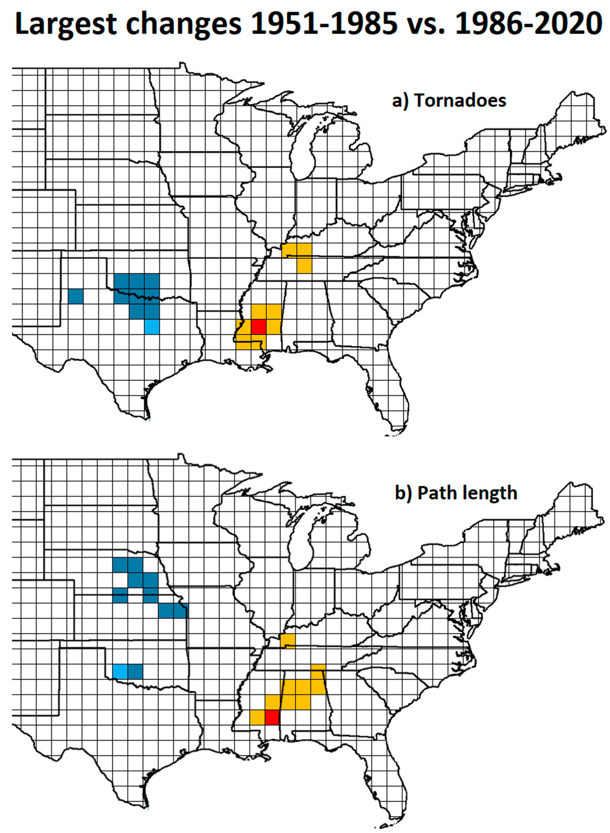


FIG. 9. The 10 grid boxes with the largest increase (orange) and decrease (blue) in (a) tornadogenesis events and (b) pathlength between period 1 and period 2. The boxes with the largest increase (red) and decrease (dark blue) are also shown.

largest increase in tornado pathlength includes the city of Laurel, Mississippi, while the box with the single largest decrease includes Elk City, Oklahoma.

6. Seasonal trends

The trend over the past few decades toward more tornadoes during the cold season (defined herein as September through February) was examined. This trend may have some association with the increase in eastern U.S. tornadoes (e.g., Childs et al. 2018). The number of F/EF1+ tornadogenesis events during each season (as previously defined) was evaluated and is plotted in Fig. 10. Tornadoes increased slightly during MAM (about 25% 1951–2020), but the largest percentage increases 1951–2020 were during DJF (102% increase) and SON (80% increase); these large percent increases may be a bit misleading, since the numbers are much smaller in the cold season than in the warm season. By contrast, summer tornadoes decreased by 37% 1951–2020.

The geographic locations of F/EF1+ tornadogenesis events by season during period 1 (1951–85) versus period 2 (1986–2020) are shown in Fig. 11 (warm season, including MAM and JJA) and Fig. 12 (cold season, including SON and DJF), smoothed using a Gaussian 3 × 3 filter. The changes between period 1 and period 2 are shown in Fig. 13. The largest number of tornadoes nationwide occurred during spring, and the classic tornado alley, centered in central Oklahoma, at least during period 1, was the most prolific tornado region of the United States. The spring maximum for the United States was still located in Oklahoma during period 2, but it was neither large nor prolific, while areas much farther east became more prolific during spring in period 2. Summer tornadogenesis events changed little over the northern United States from period 1 to period 2 but diminished greatly over Texas, Oklahoma, and Kansas (Figs. 11c,d).

Autumn overall has the least tornadoes nationwide, but there was an increase from period 1 to period 2 in autumn tornadogenesis events in the Southeast and parts of the Ohio Valley (Figs. 12a,b). Almost all winter tornadoes occurred in the Southeast United States, but their numbers increased, primarily in Louisiana and southern Mississippi, from period 1 to period 2 (Figs. 12c,d).

In total, spring tornadoes accounted for 45% of all F/EF1+ U.S. tornadoes during periods 1 and 2. This lack of change between periods is worth noting; even though there has been some redistribution from the central to the eastern United

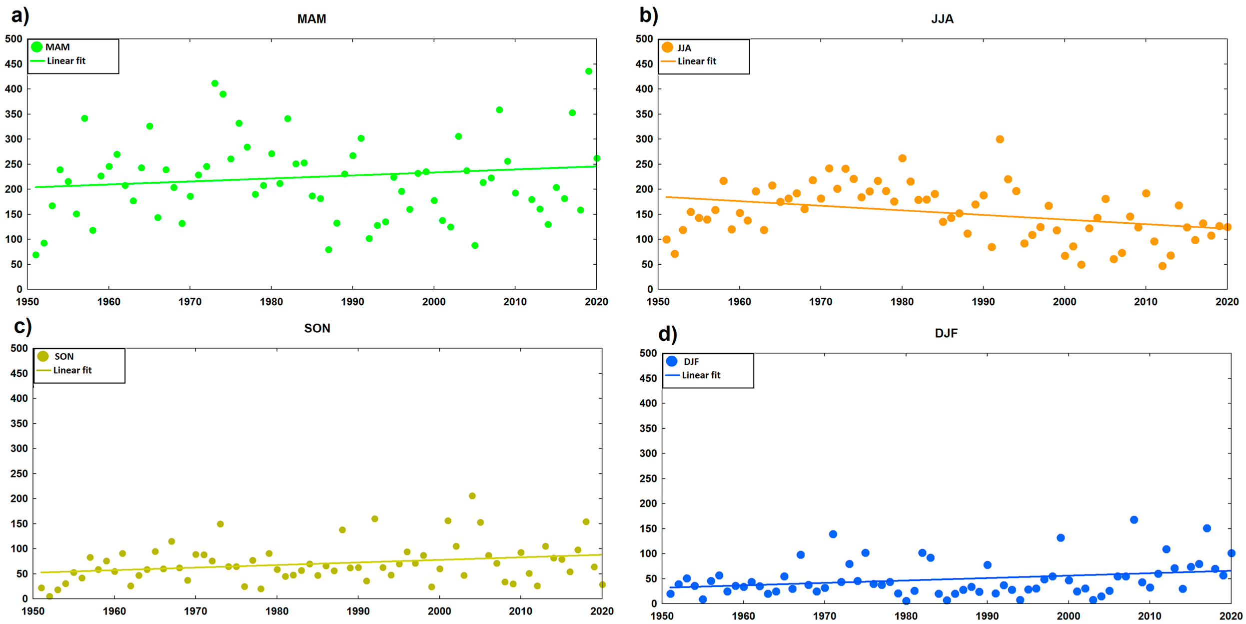


FIG. 10. Annual U.S. F/EF1+ tornadoes (1951–2020) during (a) spring (MAM), (b) summer (JJA), (c) autumn (SON), and (d) winter (DJF). The best-fit linear trend is shown in each panel.

States, summer tornadoes accounted for 35% and 27%; autumn tornadoes accounted for 12% and 17%; and winter tornadoes accounted for 9% and 11% of U. S. tornadoes during periods 1 and 2, respectively. The cold season percentage of tornadoes increased from 20% during period 1 to 28% during period 2.

The trend in significant tornadoes (F/EF2+) was examined by season. The results are shown in Fig. 14. There was a

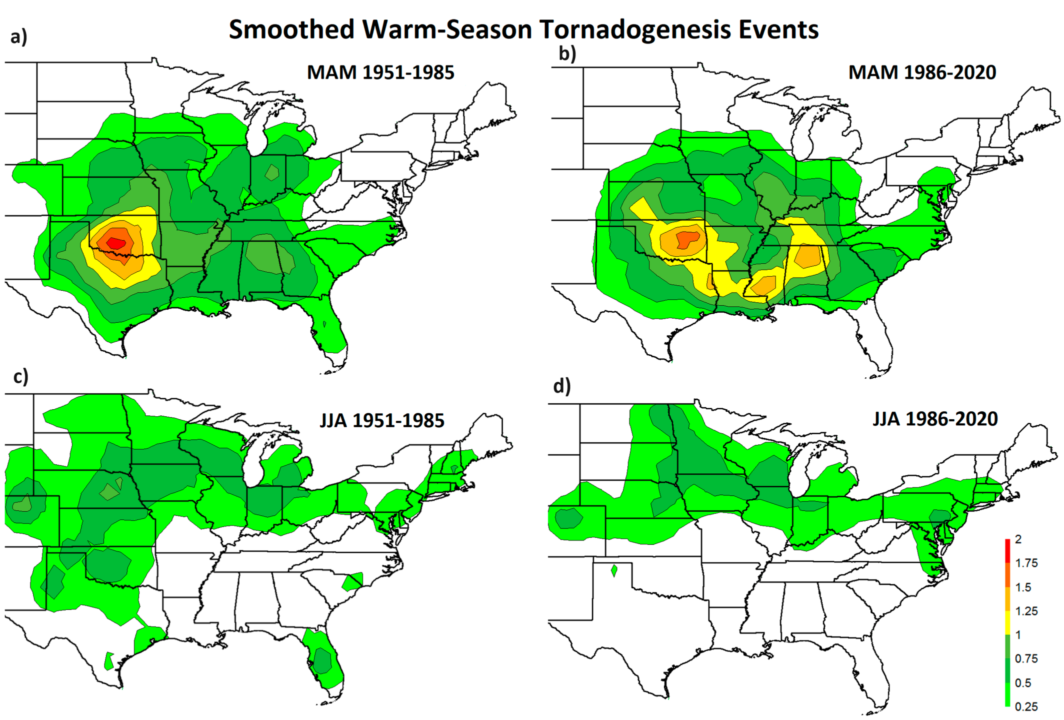


FIG. 11. Smoothed warm season F/EF1+ tornadogenesis events per 1° × 1° grid square during (a) period 1 MAM, (b) period 2 MAM, (c) period 1 JJA, and (d) period 2 JJA.

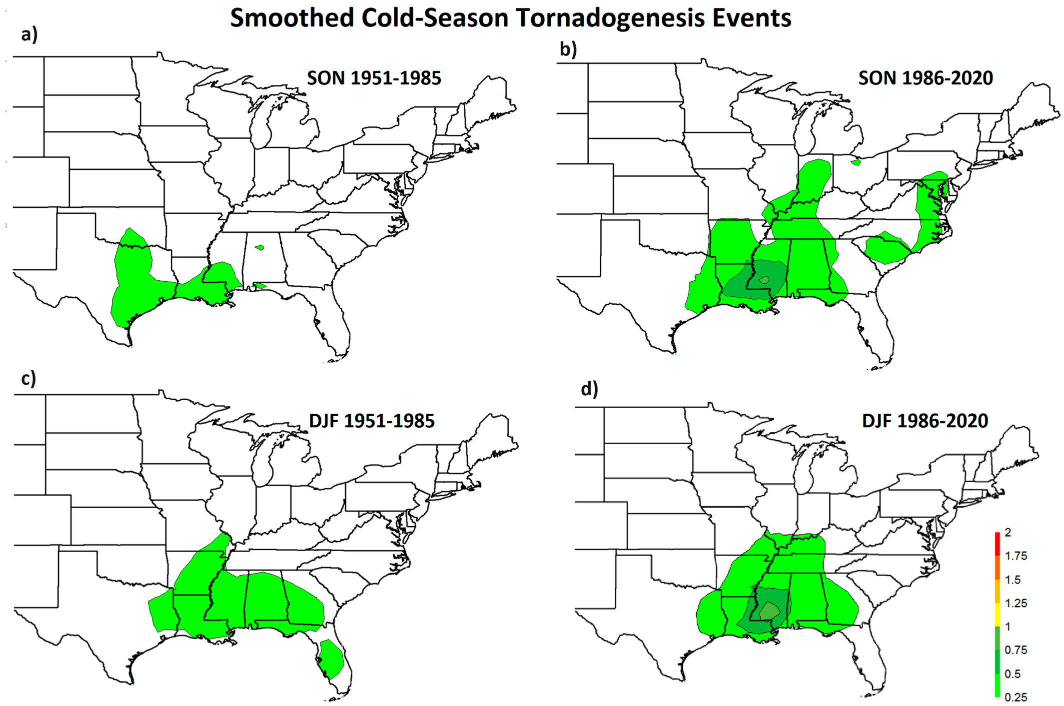


FIG. 12. Smoothed cold season tornadogenesis events per 1° × 1° grid square during (a) period 1 SON, (b) period 2 SON, (c) period 1 DJF, and (d) period 2 DJF.

decrease between 1951 and 2020 in the number of F/EF2+ tornadoes during all seasons. The largest percentage decrease was during summer, a 79% decrease in F/EF2+ tornadoes from 1951 to 2020. The magnitude of the decrease was similar during spring, but given larger numbers of F/EF2+ tornadoes, the percentage decrease was smaller at 51%. The decreases were much smaller in magnitude and percent during the cold season, with a 39% decrease in F/EF2+ tornadoes during autumn and a 27% decrease during winter. However, as discussed in section 4, the decrease in F/EF2+ tornadoes may be inflated somewhat due to changes in damage surveys and the use of the EF scale.

7. Numerical results

Geographical

Examining the numerical trends in F/EF1+ tornadoes, tornado days, tornado pathlength, and the changes in those variables by year in the east and west since 1951 (as defined in Fig. 2b) is a useful exercise (Fig. 15), especially since this subgroup of tornadoes has been shown to be the most steady since 1951 (see Fig. 1). Numerical data for seasonal trends will also be examined.

The best-fit linear trend shows that the number of tornadoes (in this section, F/EF1+ tornadoes only) was higher in the west than in the east during 1951–61. After this period, the eastern U.S. F/EF1+ tornadoes grew by 37% between 1970 and 2020, while western U.S. tornadoes decreased by 27%. In total, from 1951 to 2020, the annual number of F/EF1+ U.S. tornadoes increased from 473 to 520 (10%); there was a decrease in the west from 253 to 167 (−34%) and an increase in the east from 220 to 353 (60%).

Tornado days decreased with time in both regions, with a faster decrease in the west than in the east. While on the 1° × 1° grid, there could be tornado days in five different east grid boxes, here that only counts as one tornado day for the east. The annual number of U.S. tornado days decreased from 188 to 118 (−37%) during the period 1950–2020; in the west, tornado days decreased from 94 to 48 (−49%); and in the east, they decreased from 93 to 70 (−25%). A simple conclusion is that more tornadoes are occurring per tornado day in both regions, as has been shown in other studies (e.g., Brooks et al. 2014; Tippett et al. 2016; Moore and Fricker 2020).

Examining the linear fit for pathlength shows that it was almost evenly distributed early in the period, with 2126 km in the west and 2214 km in the east. However, pathlength was the variable where the clearest "shift" from west to east occurred. In the west, annual tornado pathlength decreased 1951–2020 from 2126 to 1383 km (−35%); in the east, it increased from 2214 to 3235 km (46%). So, the increase in eastern U.S. tornado pathlength during this 70-yr period was accounted for by a nearly equal decrease in the western United States.

As mentioned above, using the best-fit linear trend, the average annual number of F/EF1+ tornadoes increased by about 10%, from 474 to 521, during the period 1951–2020. However, the change during certain seasons, especially relative changes, was much larger. For example, spring

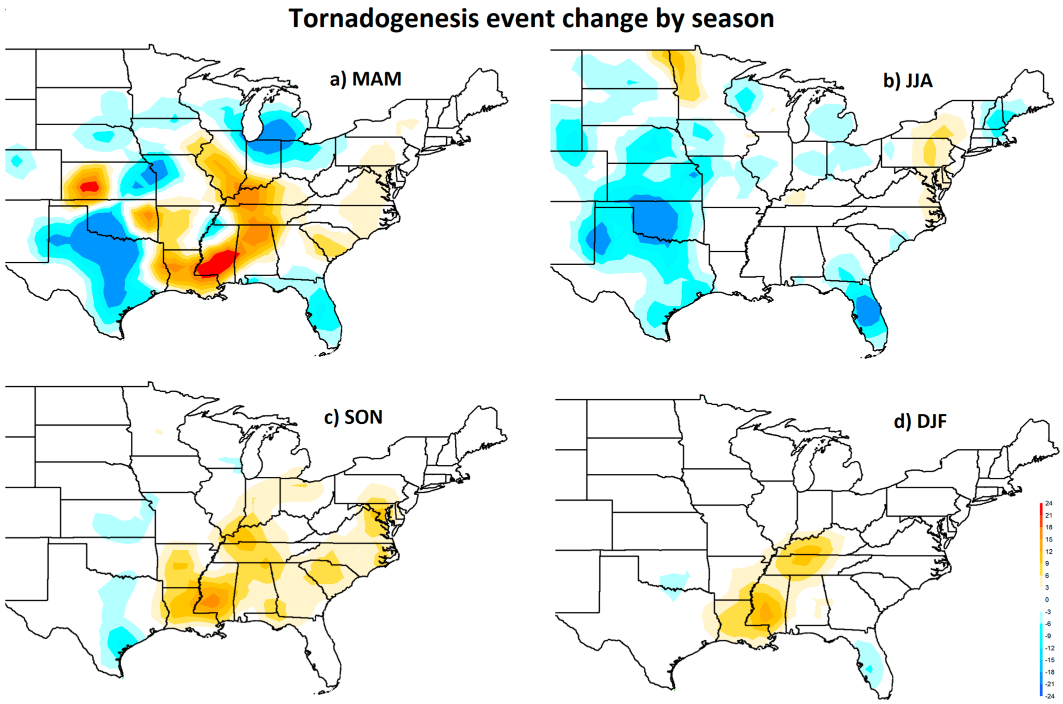


FIG. 13. Smoothed change in tornadogenesis events per 1° × 1° grid square from period 1 (1951–85) to period 2 (1986–2020) during (a) MAM, (b) JJA, (c) SON, and (d) DJF.

(MAM) annual tornadoes increased from 204 to 246 (20%), but summer (JJA) tornadoes decreased by a larger magnitude, from 185 to 121 (−34%). Annual autumn (SON) tornadoes increased from 53 to 88 (67%), and winter (DJF) tornadoes increased from 35 to 66 (103%).

8. Summary of findings

Given the steadiness of F/EF1+ tornado counts over the past 70 years and the slow decline in the numbers of F/EF2+ tornadoes, it is apparent that the perceived shift in tornado

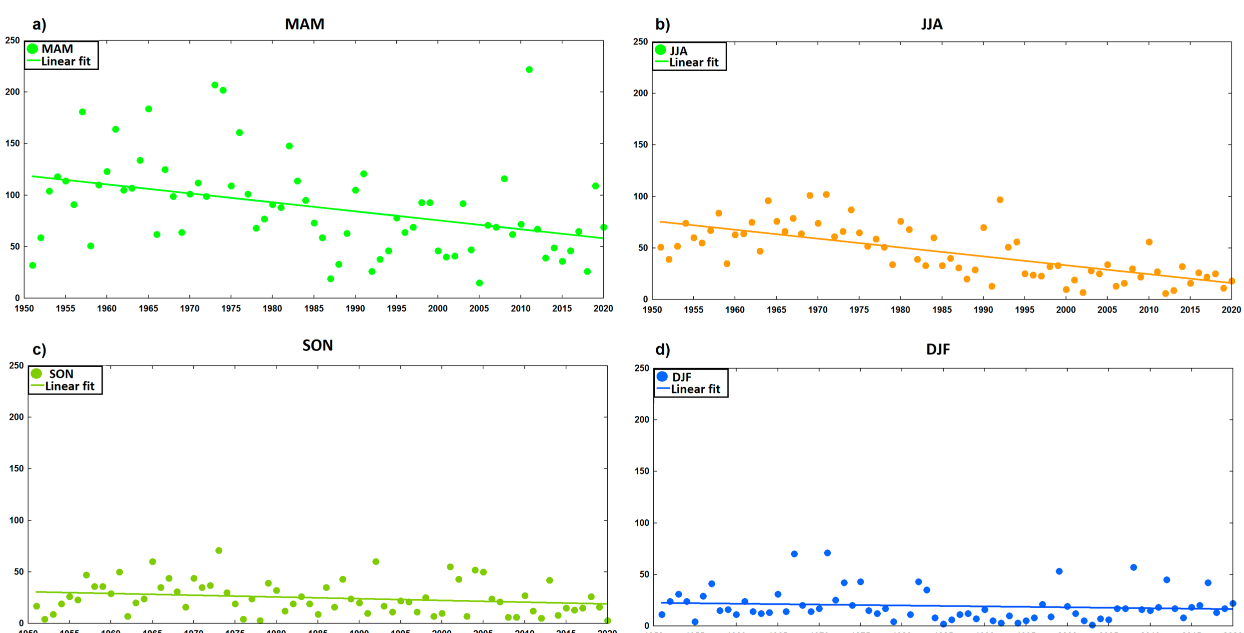


FIG. 14. Annual U.S. F/EF2+ tornadoes 1951–2020 during (a) spring (MAM); (b) summer (JJA); (c) autumn (SON); and (d) winter (DJF). The best-fit linear trend is shown in each panel.

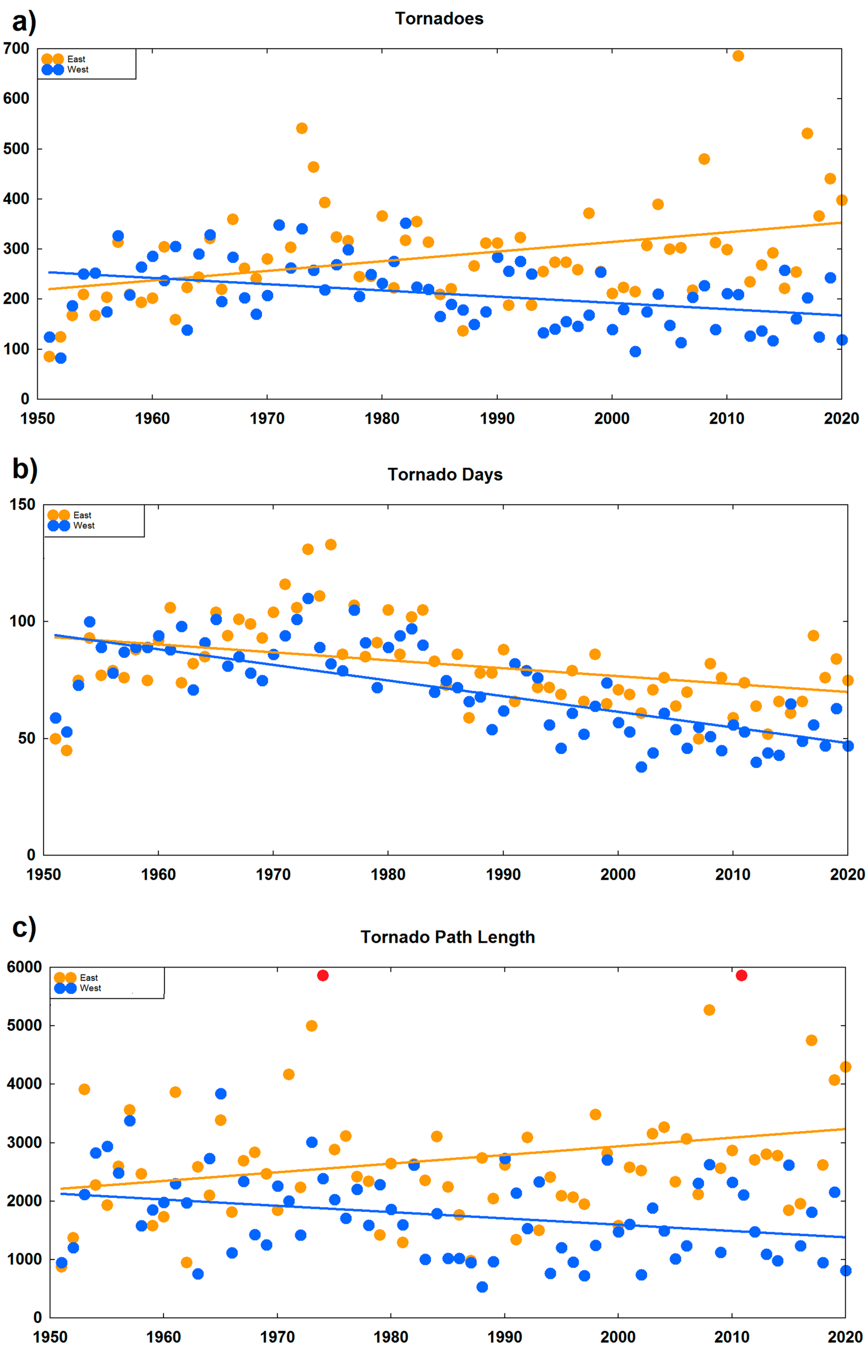


FIG. 15. (a) F/EF1+ tornadoes, (b) tornado days, and (c) tornado pathlength (km) in the eastern United States (orange dots) and the western United States (blue dots), by year. Best-fit linear trends are also shown. Note that Fig. 1 shows a relatively flat trend in F/EF1+ tornadogenesis in the United States that is composed of an increase with time in the east and a decrease with time in the west (Fig. 12a). Also, despite the number of F/EF1+ tornadoes being relatively steady since 1951 (see Fig. 1), summer tornadoes have decreased (Fig. 10b), while tornadoes during other seasons have increased (Figs. 10a,c,d).

activity from the traditional tornado alley in the Great Plains to the eastern United States. is indeed real and not only due to newly found weaker tornadoes in QLCSs and tropical cyclones (TCs) in the east. This was shown using data from two periods, period 1 (1951–85) and period 2 (1986–2020), using several metrics: tornadoes, tornado days, and tornado pathlength.

Significant tornadoes (F/EF2+) were examined since 1973, when near-real-time rating of tornadoes on the Fujita (or enhanced Fujita) scale began. The premise is that very few F/EF2+ tornadoes have been missed in the United States since 1973. Significant tornadoes, overall, have shown a decrease since 1973 by all metrics (tornadoes, tornado days, and pathlength); this could be due to a number of factors. The difference in F/EF2+ tornadoes during two 24-yr subperiods (1973–96 and 1997–2020) shows that an eastward shift in significant tornadoes and the pathlength of significant tornadoes are apparent. The overall national decrease in significant tornadoes was apparent in the data, with large decreases in the southern GP and small increases in the Southeast. However, the metric with the least decrease (1973–2020), pathlength, showed a decrease in much of the GP and an increase in much of the eastern United States, primarily the Southeast and western Ohio Valley, from 1973–96 to 1997–2020.

Examination of F/EF1+ tornadogenesis events by season using the two longer periods (1951–85 and 1986–2020) showed a national increase in tornadoes (1951–2020) of 25% during spring, but a 37% decrease during summer. Larger percent increases were during the cold season, including an 80% increase during autumn and a 102% increase during winter. Spring had the most tornadoes during both periods, and the spring maximum was located in the GP during both periods. However, spring tornadoes became spread much more evenly over mainly the southern United States during period 2, as opposed to the significant relative maximum in Oklahoma during period 1. Summer tornadoes changed little over the northern United States but diminished greatly over the southern plains from period 1 to period 2. Autumn has the fewest tornadoes, but there was an increase over time in autumn tornadogenesis events in the Southeast and parts of the Ohio Valley. Winter tornadoes, which occur almost exclusively in the Southeast, increased from period 1 to period 2. Interestingly, the percentage of tornadoes occurring during the cold season (SON and DJF) increased from 20% during period 1 to 28% during period 2, and most cold season tornadoes occur in the eastern United States.

Numerical examination of F/EF1+ tornadoes from 1951 to 2020 (without periods) showed that the annual number of F/EF1+ tornadoes nationally increased from 474 to 521 (10%), but there was a decrease in the western United States of 34% and an increase in the eastern United States of 60%. This represents a clear redistribution of tornado events from the western United States to the eastern United States Tornado days decreased with time in both regions, but the decrease was larger in the west than in the east. It appears that more tornadoes are occurring per tornado day (e.g., Brooks et al. 2014; Moore and Fricker 2020). Tornado pathlength was fairly steady from 1951 to 2020, and it was evenly distributed across the western and eastern United States in the early 1950s. But, there has been a divergence since the 1950s, with annual tornado pathlength decreasing by 35% in the west and increasing by 46% in the east; the increase in eastern U.S. tornado path during this 70-yr period was accounted for by a nearly equal decrease in the western United States.

Acknowledgments. The authors wish to thank Ernest Agee, Grady Dixon, Kevin Knupp, and Matt Bunkers for helpful discussions regarding this research. The authors also thank the anonymous reviewers, whose comments always improve the manuscript. This research was funded by NOAA via NGI Contract 191001.363513.04G.

Data availability statement. All data used in this study are available from the authors upon request via email or a letter.

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